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ABSTRACT

The work reported aims at the construction of a sufficient theory of transition in cognitive development. The method of theory construction employed is computer simulation of cognitive process. The core of the model of transition presented comprises self-modification processes that, as a result of continuously monitoring an exhaustive record of environmental interaction, construct and modify a long term model of the child and the child's world. Elements of the simulated model of transition include the representation of regularities, and avoidance of unnecessary processing, and probabilistic features representing the effects of motivational and emotional influences on learning and other processes. Main operational features of the computer simulation are a time line record of episodic memory which is self-modifying through the detection of regularities, processes of regularity and novelty detection, and the modification of the child's world model in long term memory. It is concluded that a sufficient transition theory, constructed in accordance with the general hypothesis that development is a monotone, continuous process, is capable of producing a variety of performance data which are interpretable as evidence of non-monotone, discontinuous development. (Author/RH)

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Towards a Sufficient Theory of Transition In Cognitive Development

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The enormity of attempting to construct a sufficient theory of transition in cognitive development is easily established. Such a theory must not only comprise processes capable of constructing and subsequently modifying a world model on the basis of environmental interaction but, also, provide sufficient explanations of a range of developmental phenomena identified by empirical research. Among the features which must be accounted for are the following:

(i) the fundamental ability to 'go beyond' the specific content of experience and produce behaviour which is novel in the sense that, although learned schemes are components of it, no learned scheme is responsible for fitting the components together (Pascual-Leone, 1975);

(ii) the range of individual differences in the course of cognitive development even if viewed within a framework of equifinality (Wallace, 1972; Wohlwill, 1973);

(iii) the developmental performance profiles falling within Piaget's (1941) general categories of horizontal and vertical décalage;

(iv) the occurence of apparent regression, repetition or curvilinear development (Mehler and Bever, 1967; Bower, 1978; Strauss et al., 1979; Bowerman, 1979; Carey et al., 1979);

These developmental features and the empirical research findings from which they have been derived provide much of the basis for discussion of the relative importance of continuity and discontinuity in cognitive development. The work to be reported is aimed at the construction of a sufficient theory of transition expressed in the form of a computer program and capable of producing performance characterised by these features. Its significance for the continuity - discontinuity issue is that the theory reflects the general hypothesis that development is a monotone, continuous process which gives rise to performance characterised by surface features interpretable as evidence of non-monotone, discontinuous development. In the present paper the core of the transition theory will be briefly described and an indication will be provided of the type of explanations that it provides of the developmental phenomena.

Methodological Considerations

As a preliminary to presentation of the current status of the theory there are two general methodological aspects which warrant clarification. The first of these concerns research strategy and the second centres on the employment of computer simulation and its relationship to empirically acquired data.

(i) Research strategy

This can appropriately be compared to building a bridge from both ends. It is hoped that the eventual result may be as satisfactory as Pythagoras's efforts at tunnel construction on Samos. The strategy involves a simultaneous 'top-down' and 'bottom-up' attack on the problems of theory construction. The main result of the 'bottom-up' approach to date is an information processing theory covering pre-operational and concrete operational performance on five tasks. The tasks comprise class inclusion, conservation of discontinuous quantity, transitivity of discontinuous quantity, conservation of length and transitivity of length. The final version of the theory consists of a group of running computer programs (Klahr and Wallace, 1976). The current state of the 'top-down' work is the subject of this paper.

(ii) The role of computer simulation

The expression of a cognitive psychological theory in the form of a computer program serves an important evaluative function since it enables confirmation of the sufficiency of the theory to account for the task performance or internal processing that it purports to explain. The contribution of computer simulation extends beyond the establishment of sufficiency when a theory includes both deterministic and probabilistic features. In these circumstances it is extremely difficult to predict the results of complex interactions between the features and the effect of adjustments of the values of the variables. Computer simulation is of great assistance in resolving these difficulties.

Computer simulation is in no sense a substitute for experimental investigation. The two characteristically interact with empirical results being reflected in the structure of the theory and, thus, the computer program, while writing and running the program point up lacunae in the theory which provide themes for further experimentation. In the work to be reported

empirically derived data is, also, being used as input to the computer program.

A Model of Transition

(i) The representation of regularity

The detection of regularities in environmental interaction and their incorporation in the child's representation of his world in long term memory (LTM) are central features of the model of transition. The processes of detection and incorporation are carried out by generally applicable self-modification processes which are assumed to be part of the child's innate endowment. Their operation is governed by a least-effort or processing-economy principle. The rationale for its adoption is presented in a detailed discussion of memory architecture by Klahr and Wallace (1976). In brief, the memory architecture is considered to combine short term memory (STM) buffers or workspaces of severely limited capacity with a long term memory (LTM) which for practical purposes may be regarded as infinite. These characteristics place a high premium on making the symbols processed as information laden as possible and on avoiding any unnecessary processing.

The detection of regularities in the child's interaction with the environment provides the basis for increasing the information load of individual symbols. When a consistent sequence of processing is identified an addition may be made to the LTM world model. This consists of a conjunction of the processes involved in the sequence and is stored at a location represented by a single symbol. In future when the appropriate context is encountered the processing sequence occurs as a result of the activation of the new aggregated representation with a consequent reduction in the symbol manipulation required in STM. In pursuit of further processing economy a general strategy is followed of extending as far as possible the area of application of each new aggregated representation added to LTM. This process of generalisation occurs both during its construction and subsequent operation. If inappropriate extensions are attempted the resulting negative feedback from the environment leads to modification of the activation conditions of the representations to enable the necessary discrimination to take place.

The general effect of this extension strategy must be viewed in the context of the LTM structures which provide a basis for representation of the world. LTM is regarded as being heterarchical rather than hierarchical, (Baddeley,1978). That is to say it has a disconnected graph structure made up of a large number

of subsidiary networks or sub-systems. Sub-systems are constructed by the processes of regularity detection and aggregation representation already described. They bear a broad resemblance to the 'frame' type of experiential grouping (Minsky, 1975) since they correspond to particular recurring contexts and control of behaviour shifts from sub-system to sub-system with movement from situation to situation. In conjunction with the extension strategy the heterarchical LTM structure creates a situation in which resolution of conflict arising from 'domain overlap' assumes a key function in developmental transition. When a new aggregated representation is added to LTM a sub-system is augmented and set in an extension mode. This leads to attempts to generalise its application into the domains of other sub-systems relevant to related contexts. Before environmental feedback leads to discrimination between appropriate and inappropriate extensions the domain overlap phase may adversely affect performance due to over-generalisation of the sub-system operating in the extension mode.

(ii) The avoidance of unnecessary processing

In the extension strategy processing economy is sought by maximising the area of application of new aggregated representations added to LTM. This process of generalisation depends on the preceding processes of differentiation and integration which underlie the construction of aggregated representations. An alternative method of achieving economy in processing is to avoid engaging in unnecessary differentiation and integration. In the model of transition this objective is pursued by adoption of the general principle that in interaction the environment should be coped with in as large or global units as possible consistent with the preservation of effectiveness. Breaking up or analysing the environment by differentiation into smaller or more finely grained units is only resorted to when negative feedback from the environment indicates that it is necessary.

The empirical effects of the operation of this principle have been described in detail elsewhere (Klahr and Wallace, 1976; Wallace, 1979). It underlies the tendency of young children to process their environment in terms of global objects rather than the values of particular dimensions characterising objects until negative environmental feedback prompts a move from a global orientation to operating on the basis of separate dimensions. Avoidance of unnecessary differentiation and integration also underlies the general assumption that, until feedback indicates otherwise, transformations leave the qualities of objects unaltered. As these examples indicate, the principle applies regardless of whether the initial global state is an aspect of innate endowment or the result of earlier episodes of differentiation and integration.

A further general method of avoiding unnecessary processing hinges on the detection of consistent sequences in environmental interaction. The addition to LTM of representations of consistent sequences paves the way for the elimination of redundant processing by monitoring the extent to which interactive effectiveness would be impaired by the omission of a section of the sequence. Conservation of quantity emerges in this fashion. Consistent sequences are used to predict the effect of transformations on the relationship between the initial and resultant collections. The relationship is simply read off the sequence without carrying out quantifications after the transformation. The predictions are verified by quantitative comparison with the initial collection. Success in this prediction results in confirmation that quantification of the collection after the transformation and the subsequent quantitative comparison constitute unnecessary processing and may be eliminated.

(iii) Introduction of probabilistic features

The modal aim of modelling in cognitive psychology is the construction of theories entirely concerned with psychological processes and expressed in deterministic terms. The most common reason for the introduction of probabilistic features is to temporarily bridge gaps in a theory where the underlying processes have not yet been determined. In the model of transition probabilistic features have been introduced on a permanent basis. This has proved necessary due to aspects of inductive learning which are more amenable to explanation as neurophysiological/neurochemical processes rather than psychological processes. It is, also, essential if the model is to have the capability of representing the effects of motivational and emotional influences on learning and other processing. This provision is conspicuous by its absence from current LTM models.

Having outlined the general principles governing the structure of the model of transition this brief description will conclude by providing an indication of its main operational features.

(iv) The time line

As indicated above, the transition processes are responsible for the construction and modification of the LTM world model. Discharging this function requires the ability to monitor the results of environmental interaction. The means adopted is a time line or episodic memory which contains a sequential record of the child's activity. If any regularities exist in interaction with the environment they are represented in the time line. Self-modification takes place

through the detection of this regularity by the transition processes and the subsequent addition to LTM of processes which will capitalize upon it.

The mode of representation of regularity in the time line is directly derived from the nature of the LTM world model. This is composed of a large number of networks or sub-systems. All of the networks are made up of productions and production systems which are the basic representational units. A production is a rule which consists of a condition and an associated action. The condition tests the current contents of the STM buffer which governs activation of the production. If the condition is satisfied then its associated actions are carried out changing the current knowledge state as reflected in the contents of the STM buffers. A collection of productions which serve some specific function is called a production system. Adoption of productions as the unit of cognitive analysis renders the LTM network homogeneous and entirely composed of potentially active units. Consistent with Newell and Simon's (1972) approach, there is a single type node in LTM at which is stored the complete representation of each production or production system. When additional representations are required anywhere in the networks, they take the form of tokens which are pointers to the location of the appropriate type node.

Each node in the LTM network represents the definition of a potentially active unit of knowledge or feature of the world model. In Figure 1, for example, an object is represented by a type node at which is stored a production system, PSOB3, composed of tokens representing a process definition of the object constructed as a result of perceptual experience of it during environmental interaction. In addition to this process definition or definition list each type node has two other major components, an experience list and a description list. The nature and function of these features of node structure will become evident as the mode of operation of the time line and the regularity detection processes are described.

Figure 1 about here

The time line record is compiled concurrently with the flow of processing activity. As each type node (which can, of course, be the location of a single production or a production system) is activated, a token pointing to the type node and tokens representing the predicate which satisfied the conditions for activation of the production system are placed in the time line. At the conclusion of its activity tokens representing the output produced by the production system are also inserted in the time line before the type node becomes inactive and the episode terminates.

Examples of two stretches of the time line record are provided in Figure 2 -(1) and (3). These segments represent the type of processing sequence arising from everyday events which may contribute to the emergance of identity conservation of discontinuous quantity (Klahr and Wallace, 1976). A child repeatedly quantifies a collection of two shoes while changing their spatial location and engages in externally prompted comparison of the results. The mode of quantification employed is subitizing, the process which underlies the experience of apparently immediate awareness of the number of objects in collections. The time line record is written in a close approximation to PSG, a computer language constructed by Newell (1972). This is employed as a convenient method of simulating an internal, non-verbal, non-figural semantic code in which all processing in the LTM network proceeds. The first line in the initial time line segment records an activation of PSVS, the type node representing the production system responsible for subitizing. The predicate which satisfied its activation conditions on this occasion is an active goal or objective of applying subitizing to a collection of shoes, (*GOAL SUBIT SHOES). The output resulting from operation of the production system is an indication that the goal has been successfully achieved ($ GOAL SUBIT SHOES) and a representation of the quantity of shoes derived by subitizing (QSUBTWO SHOES).

Due to the developmental importance of feedback on the effectiveness of interaction each type node has the ability to check the output produced as a result of its activation on each occasion against a representation of the general nature of the end state which it expects to produce. If a mismatch occurs an entry representing this negative feedback is placed in the time line for the future attention of the transition processes.

(v) The process of regularity detection

The initial step in appropriate self-modification of the LTM world model is the identification of stretches of the time line sequence which constitute significant, novel experience. An experience list which is a feature of each type node provides a means of assessing novelty. Each entry on the experience list comprises a sequence of tokens beginning with the token for the type node at which the experience list is stored. The sequence of tokens represents a description of a sequence of episodes representing states and transformations which has been detected with a significant degree of consistency in previous processing of the contents of the time line. The general structure of an experience list is indicated in Figure 1 -C. Figure 2 -(2) and (4) includes two specific examples of experience list entries. As already indicated these arise from the operation of the subitizing type node,

PSVS. PSVS1 is a sequence commencing with a record of the activation of PSVS and representing a consistent sequence of episodes arising from quantification and requantification of a collection of shoes.

The process of novelty detection begins with the experience list of the type node corresponding to the first token in the segment of the time line being reviewed. In turn the sequences on the experience list are compared with the time line. If one of the sequences matches a stretch of the time line it does not represent novel experience. A token for the experience list sequence is substituted for the stretch in the time line. The next token in the time line after the successfully matched stretch identifies the type node which supplies the experience list for the next comparison phase. Any stretches of the time line segment which have not been successfully matched at the conclusion of the series of experience list comparisons are regarded as novel. These form the input to the processes concerned with significance determination.

The decision as to whether any of the novel stretches of the time line are to be regarded as significant experience is entirely determined by the degree of consistency in the processing sequences they represent. The consistency detection procedures included in the self-modification processes are relatively simple in accordance with the conviction that characteristic features of environmental interaction tend to the production of time line content that facilitates consistency detection. An obvious example is the apparently innate disposition to engage in repetition of sequences of behaviour.

Figure 2 about here

The search for consistency begins with a qualitative scan of the entire time line segment being reviewed to detect salient features which might provide promising starting points. A detailed account of this process cannot be provided but among features attended to are tokens representing the attainment of end states or goals with a weighting indicating high motivational and emotional 'importance'. The goals attained in the time line segments in Figure 2 -(1) and (3) have a zero weight on this criterion, ($GOAL 0 SUBIT SHOES). The next step involves marking all of the episodes in the time line segment which contain tokens for the most salient feature detected and also satisfy the general criteria for matching episodes. The areas of the time line around these episodes are submitted to the consistency detection processes.

Consistency detection is the aspect of the transition model which contains probabilistic features. The first of these is the M(atching) I(ndex) C(riterion) (0-1.0). The MIC is accorded a constant value for each individual and is regarded as varying between individuals. It is considered to reflect the operation of the

neurophysiological/neurochemical rather than psychological level of functioning. The MIC determines the level of agreement between tokens required before two episodes match and the level of agreement between episodes before two episode sequences are regarded as a match. A key feature of the MIC for the transition process is that it permits partial matching. Provided that the surrounding context within an episode or in an episode sequence is sufficiently consistent to satisfy the prevailing MIC value information on the correspondence in the occurrence of apparently mismatching tokens and episodes is incorporated into the representation of consistent sequences. This information is stored on ANYOF lists and, as will become apparent below, performs a crucial developmental function.

The decision on whether the regularity detection process has constructed a sequence representing a significant level of consistency hinges on the C(ritical) C(onsistency) L(evel). The CCL is a second neurophysiological/neurochemical variable representing sensitivity to consistency. It is a critical dimension of individual differences in inductive learning and, unlike the MIC, also exhibits intraindividual variation between time line review periods. The CCL reflects both the number of time line stretches and the degree of agreement between them which must be subsumed by a sequence before it is considered to be significantly consistent. During the regularity detection process a c(urrent) c(onsistency) l(evel) based on the same two variables is computed at each step in sequence construction. When the value of the ccl ceases to rise attempts to subsume additional time line stretches within the current sequence are discontinued and the ccl is compared with the CCL. If ccl > CCL significant novel experience has been detected and the sequence in its final form is added to the experience list of the type node corresponding to the first token in the sequence. A token for the newly created experience list sequence is substituted for all of the corresponding stretches of the time line and a new phase of consistency detection commences based on the next entry in the list of salient features.

When the list of salient features is exhausted the review of the time line terminates with an adjustment of the CCL in the light of the results of the search for consistency. This adjustment takes place within a range of CCL values characteristic of the individual. Successful consistency detection leads to an increase in CCL, failure produces a reduction. As the size of the increment or decrement is determined in accordance with the current adaptation level the effects of specific degrees of success and failure vary from review to review.

(vi) The experience list review

The addition of a new consistent sequence to an experience list does not immediately lead to modification of the LTM world model. The influence of experience list sequences on LTM is determined by their success rate in matching stretches of time line content during the phase of the review process aimed at identifying familiar experience in the service of highlighting the results of novel interaction. The matching process when an experience list sequence is compared with a stretch of the time line is identical to that employed when two novel stretches in the time line are compared in the search for consistency. A series of successful matches has two important consequences. The saliency of the sequence within the experience list steadily increases. The relative saliency of sequences on an experience list is based on a ccl value for each of them derived from the results of comparing them with the time line. Additions to the sequence may, also, occur. These may take the form of increasing the number and/or length of ANYOF lists or the length of the sequence itself by interpolation or extrapolation of additional episodes.

Both of these results of a series of successful matches is illustrated in Figure 2 -(2) and (4). A comparison of the two versions of the sequence PSVS1 reveals an increase in its saliency or ccl value from the initial 0 to 7. The sequence has also increased in length as a result of the interpolation of additional episodes such as (ANYOF (*INT.1) (BLACK.4)). This reflects the incorporation into the experience list sequence of further detail included in the time line as a result of a continuation of the child's experience with the shoes. The weight 4 indicates the number of occasions on which BLACK has figured in a match between the experience list sequence and stretches of the time line record.

Decisions on the appropriateness of LTM modification are taken when an experience list sequence as a result of a series of time line comparisons reaches a point at which ccl exceeds the current value of CCL. It is not possible to cover all aspects of the review process that occurs at this juncture. Only those features which are directly relevant to the explanation of the developmental phenomena will be briefly described. First among them is the processing of ANYOF lists.

The entries on the ANYOF lists included in a sequence which has attained the criterion saliency level are initially submitted to a winnowing process to remove individual tokens and complete lists with relatively low frequencies of occurrence. This process explains the deletion of SHINY from the second

version of the PSVS1 experience list sequence in Figure 2 -(4) in the course of the construction of the new production to be placed at the PSQC type node. With the winnowing accomplished an attempt is made to discover one or more type nodes representing a higher level of generality which subsume members of the ANYOF lists in the specific context represented by the sequence. The information necessary to carry out this operation is a feature of every type node in LTM. If a node representing a higher level of generality is discovered its token is substituted in the ANYOF list for the tokens of the members which it subsumes.

This generalisation process may directly give rise to aggregation by initiating the addition to LTM of a new type node representing a combination of a number of existing type nodes. This is made possible by a further feature of type node structure. At each type node a record is maintained of other nodes which, on the basis of ANYOF list reviews, appear to perform an equivalent function to it in specific contexts. This record of functional equivalence covers both operator and object equivalence, both occasions when the type node is active processing other tokens and those in which its tokens serve as passive input to other nodes.

In Figure 1 an entry on the description list of the PSOB3 type node indicates its functional equivalence to the objects represented by the PSOB7 and PSOB12 type nodes when input to the production system PSA in pursuit of the objective represented by GOAL X. When processing of the equivalence records of two or more type nodes reveals a significant level of functional correspondence between them a new type node representing a combination of their operational characteristics is added to LTM. A significant level can be attained as a result of the identification of a large number of nodes with a narrow band of equivalence or a small number of nodes with a broad band of equivalence. The entry PS.ROUND on the description list of PSOB3 in Figure 1 provides an example of the former. It indicates that the PSOB3 type node has participated in the process culminating in the addition to LTM of a new type node representing the value ROUND.

Having undergone a review of ANYOF lists a salient sequence is submitted to further processing aimed at identifying and storing novel information concerning relationships between type nodes. This is intended to contribute to processing economy in the future by removing the need to repeat the processing if access to the relationships is required. An example is provided in Figure 1 by the entry PSWEIGHT ($\overset{Q}{>}$ PSOB6) on the description list of PSOB3. This stores for

future reference the result obtained when PSOB3 and PSOB6 formed the input to PSWEIGHT, a production system concerned with the determination of a specific range of quantitative relationships.

The objective of achieving processing economy also underlies an examination of the sequence aimed at detecting redundant information processing. The extent to which interactive effectiveness would be impaired by the omission of a section of the sequence is investigated. The general process will be illustrated by reference to conservation of quantity which emerges in this fashion. In Figure 2 -(4) the second, more detailed version of the experience list sequence PSVS1 has attained the criterion saliency level required and is reviewed as a source of possible LTM modification.

The examination for redundant processing begins with a search for repetition of the activation of type nodes in the sequence. This leads to the discovery that the operation of PSQC may be unnecessary since it incorporates a second activation of the subitizing type node, PSVS, which began the sequence. As a consequence the new production listed in Figure 2 is constructed and added to the PSQC type node. If the events included in the PSVS1 sequence occur again this addition to LTM will produce the quantitative comparison result without further activation of the quantitative comparison process. Such additions to LTM do not enjoy permanent status until subsequent processing confirms that economy has been achieved without impairment of the effectiveness of environmental interaction.

Subject to the cumulative effects of earlier phases in the review process a salient sequence may itself provide the basis for the addition of a new type node to LTM. The new node is defined in terms of the productions and production systems responsible for the appearance of the consistent sequence in the time line. This addition represents significant aggregation since results previously involving the identification and activation of a number of type nodes will in future be achieved as a result of a single LTM search and node activation. An attempt is, also, made to generalise the application of the new node. The type nodes of all of the productions and production systems which it includes as both operators and objects are searched to discover if they have been subsumed by more general type nodes in the specific context represented by the salient sequence. If this search is successful tokens for the nodes representing a higher level of generality are incorporated in the definition of the new node.

In this brief account of the transition model emphasis has been placed on features relevant to the explanation of the developmental phenomena listed at the outset. The features include the interaction of the processes of aggregation and generalisation, the extension strategy, the heterarchical structure of LTM, the avoidance of unnecessary processing and the function of the MIC and CCL parameters. In the final section of this paper the import of the model for each of the developmental phenomena will be briefly discussed.

DISCONTINUOUS PHENOMENA AND CONTINUOUS DEVELOPMENT

(i) The emergance of novel behaviour

The core of the model of transition which has been presented comprises self-modification processes that as a result of continuously monitoring an exhaustive record of environmental interaction construct and modify a LTM model of the child and his world. On the psychological plane the fundamental process of development is continuous. On the neurophysiological level it produces discontinuities represented in the binary states governed by the values of the MIC and CCL parameters.

The general source of performance data interpretable as empirical evidence of discontinuity in development is additions to LTM resulting in alterations in the child's competence which are subsequently reflected in observable performance. All novel behaviour can from this standpoint be regarded as evidence of specific discontinuities. The ability to 'go beyond' the specific content of experience is an essential feature of the model of transition. The key aspects underlying the acquisition of competence that produces novel performance are the partial matching in consistent contexts which gives rise to the formation of ANYOF lists and the emphasis on generalisation in the construction and subsequent operation of new representations added to LTM. No learned scheme is responsible for such additions to LTM since the self-modification processes concerned are attributed to innate endowment.

This is an appropriate point to mention certain broad similarities between the model of transition and the concept of 'equilibration'. Piaget (1959) makes a distinction between the acquisition of content and structure in intellectual development. The former is brought about by learning on the basis of experience while the latter, which comprises the active formation

and reorganisation by the child of the logical structures necessary to cope with the content derived from experience, is identified with the process of equilibration. Although by no means an exact parallel, the distinction between the phases of recording significant novel experience in the time line and subsequently reviewing salient sequences with a view to LTM modification does reflect the principle that specific learned experience does not directly dictate the nature of the LTM world model. The assumption that innate self-modification processes of completely general applicability are responsible for its construction is consistent with Piaget's distinction between the process of equilibration which is presumed to be innate and structures such as the groupings of operations that are constructed in the course of development as a result of interaction with the environment and the functioning of the equilibration process.

(ii) Individual differences and equifinal states

A general view of cognitive development derived from the type of performance data generated by the model of transition would feature both widespread individual differences and developmental states traversed by all children. The former stem from the effects of specific variations in environmental experience interacting with individual differences in MIC level and in the range of CCL values. The latter arise from the interaction of major consistencies in environmental experience common to all children in a cultural or sub-cultural group with the innate self-modification processes in a fashion which overrides variations in the MIC and CCL parameters.

In the general picture of development that emerges the developmental states common to all children can be conceptualised as nodes in a network. The paths converging on the nodes represent differing developmental routes followed by individual children. These common or equifinal states may be relatively broad in scope and represent subsets of concrete operations (Wohlwill, 1973) or relatively narrow and confined to a single cognitive skill such as conservation of discrete quantity (Wallace, 1972). In either case the developmental processes underlying their appearance are the same. Equifinal states give rise to the performance data most frequently cited in support of the existence of major qualitative discontinuities or stages in development.

The broad characteristics of cognitive development derived from the model of transition remain unaltered across cultural and sub-cultural variations. Individual differences and common or equifinal states still emerge. Environmental variation, however, may alter the range of cognitive skills included in the equifinal states. It may, also, produce differences in the situational conditions governing the activation of particular cognitive skills or lead to the construction of cognitive skills that are functionally equivalent but differ in their process definitions (Cole and Scribner, 1974). The nature of the innate self-modification processes and the continuous monitoring of the record of environmental interaction remain constant across cultural or sub-cultural variation.

(iii) Horizontal and vertical décalages

The widespread appearance of the types of developmental performance profiles associated with the Piagetian labels horizontal and vertical décalages is predicted by the model of transition. It is attributable to the processes which determine the range of applicability or domain of the representations in LTM and to the context based matching and individual differences in MIC and CCL that govern the combination of representations to create new type nodes.

In the case of horizontal décalage the transition model offers two complementary explanations. The first ascribes the phenomena to the construction and addition to LTM of two or more entirely distinct representations of the same principle. The necessity for multiple derivation and representation of the same principle arises from the failure of the self-modification processes to produce a sufficiently generally applicable initial version or to subsequently increase its scope by appropriate combination with sequences derived from other content areas. This may occur in areas in which it is difficult for an observer to comprehend the situational features that impede the operation of the generalisation and context matching processes. An excellent example of this situation is provided in the discussion of the developmental relationship between conservation of discontinuous quantity and conservation of continuous quantity by Inhelder et al. (1975).

In the second explanation the scope of the initial version of a principle is subsequently increased by appropriate combination with sequences derived from other content areas and an appearance of developmental discontinuity in performance arises from the time lapse required for acquisition of the necessary experience and the subsequent processing which produces this generalisation. Both the nature of the experience and the processing may vary. In the case of conservation, for example, a version of the principle in the form of a production eliminating redundant processing may be initially derived via a quantification sub-system, such as subitizing, and subsequently generalised in incremental steps to the operations of another quantification sub-system such as counting. This occurs as a result of a series of successful comparisons with a number of salient sequences of relatively narrow applicability added to experience lists as a consequence of the employment of counting. Alternatively, if protracted environmental interaction gives rise to an experience list sequence of broad generality the same result may be produced by a single successful comparison. Either of these sequences of events would give rise to a similar time lapse.

Figure 3 about here

An illustration of the process of combination and the effect of variations in scope is provided in Figure 3. As in Figure 2 the events presented are the consequence of interaction with specific environmental features, namely a pair of shoes. The sequence of events continues from the situation produced in Figure 2 -(5). Initially, a production representing the conservation principle but confined in its applicability to the operation of subitizing on shoes is a feature of the definition list of the PSQC type node. In Figure 3 -(1) further experience with collections of shoes has resulted in the addition of the sequence COU01 to the experience list of the type node defining counting, PSCOUNT. Since the ccl of 10 satisfies the current saliency criterion this sequence undergoes the review process and redundancy elimination is attempted. This reveals that the operation of PSQC may be unnecessary since it includes a second activation of the counting type node, PSCOUNT, which began the sequence.

Before a new production is constructed a check is made to see if an already existing production can be generalised to cover the situation represented in the experience list sequence. This process involves a comparison of the experience list counting sequence with the subitizing sequence which gave rise to the already existing production. As Figure 3 -(2) indicates the subitizing sequence is stored on the description list of the PSQC type node. Since the comparison results in a successful match the new extended

version of the production in Figure 3 -(3) is added to the definition list of PSQC. The new version is still confined in scope to dealing with pairs of shoes but now subsumes both the subitizing and counting quantification sub-systems. If the interactions between environmental experience and individual MIC and CCL values resulted in development proceeding by a large number of small increments of this type construction of a representation of the conservation principle with general applicability would be a very protracted process.

The first explanation offered for horizontal décalage can, also, be adduced to account for the performance data regarded as evidence of vertical décalage. In cases falling under this heading the context matching processes may be unable to detect the underlying structural similarities between situations due to the wide disparity in their content features. As a consequence, an entirely distinct process of representation construction and addition to LTM takes place and no subsequent combination of type nodes is possible below the level of abstraction represented by psychological theory.

(iv) Curvilinear or U-shaped development

The attempt to construct a model of transition sufficient to explain monotone development has resulted in the inclusion of four aspects of the model conducive to the appearance of curvilinear or U-shaped developmental phenomena. Two aspects are relevant to the situation in which the U-shaped development is defined by three successive performances on an identical task. In the remaining two, similar rather than identical tasks are employed.

The strategy of avoiding unnecessary differentiation and integration by adopting as a general principle that the environment should be processed in as global units as possible has two negative consequences. In some cases the level of differentiation represented by the global state may be totally incompatible with effective environmental interaction; in others it may lead to success in coping with some but not all aspects of a content area. For the present purpose the latter situation can be regarded as an overextension of the domain of a child's initial method of coping with an aspect of the environment. Such overextension will result in negative environmental feedback leading to an attempt to derive a satisfactory method of coping. This proceeds by means of an increase in the level of differentiation achieved via the regularity detection processes and culminating in the addition of a new method of coping to the child's repertoire in LTM.

Consistent with the extension strategy an attempt is made to generalise application of the new method as far as possible across the relevant context. This, in turn, may result in overextension if it is applied to aspects of the content area for which the initial rather than the new method is appropriate. Resolution of this situation involves removal of the overlap between the domains of the two coping methods. This is brought about by environmental feedback which enables discrimination of their respective areas of applicability and appropriate modification of their activation conditions. The sequence of developmental steps outlined would give rise to U-shaped performance data with successive administrations of a task falling within the domain of the initial method of coping.

The second source of U-shaped performance data on identical tasks is much more sensitive to the specific timing of the data gethering and, as a consequence, is much less likely to be detected. Creation of a new type node in LTM either as a consequence of ANYOF list processing or on the basis of a salient sequence involves a considerable amount of processing of existing type nodes to obtain the necessary information. Task performance controlled by any of these type nodes might well be adversely affected if the data was collected concurrently with the process of new node creation. This very temporary regression would result in a short lived U effect.

The two remaining aspects of the transition model to be considered can be distinguished from those relevant to the identical task situation in that they give rise to regression in performance which is apparent rather than real. Apparent regression arises from a mismatch between an observer's expectations of children's level of performance across tasks deemed to be similar and the nature of the sub-systems or subsidiary networks in LTM which govern the nature of the children's responses. Failure to take account of the effect of a heterarchical LTM may result in the employment of test situations which are considered to be variants of the same task but actually depend on the activation of different sub-systems for successful performance. Since relevance to closely related contexts is no guarantee that sub-systems will develop at the same rate, apparent regression may be observed if a task variant tapping a more swiftly developing sub-system is administered to a child then followed by a variant leading to the activation of a more slowly developing sub-system. An example of the type of sub-system relationships which may give rise to such observations is provided by the development of the processes underlying conservation of discontinuous and continuous quantity (Klahr and Wallace, 1976). An analysis in sub-system terms of the demands

of the tasks employed by Mehler and Bever (1967) in obtaining their famous U-shaped data is presented by Wallace (1972). This indicates that they not only call upon distinct sub-systems but on occasions activate two or more sub-systems within a single task.

Consideration of the hetararchical LTM structure underlying performance highlights the importance of the MIC and CCL parameters. Variations between individuals in the value of the MIC and the range of CCL values may produce marked differences in the rate of development of sub-systems and in the location of the boundaries between sub-system domains. Their importance is emphasised by the nature of the second source of apparent regression. Like its predecessor this hinges on the observer's definition of task similarity and the performance expectations arising from it.

A specific example of the type of regression involved has been provided by Bower (1978) in his explanation of the apparently developmentally regressive effects of thorough training. The general sequence of events underlying the observations is as follows. A child's experience of a situation results in the detection of a consistent sequence in the time line and its incorporation in an experience list. If the experience is protracted the level of detail in the time line representation of the same sequence of events increases greatly. This effect is particularly marked in individuals with relatively high MIC and CCL values. This increase, in turn, results in an increase in the specificity of the experience list sequence as comparison with the time line content proceeds. A minor example of the effects of this process is provided in Figure 2 -(2) and (4) in the increase in the level of detail between the first and second versions of the experience list sequence PSVS1. This occurs in response to an increase in the level of detail represented in the time line as continued experience provides the child with an opportunity to perceive more of the detail in the external situation.

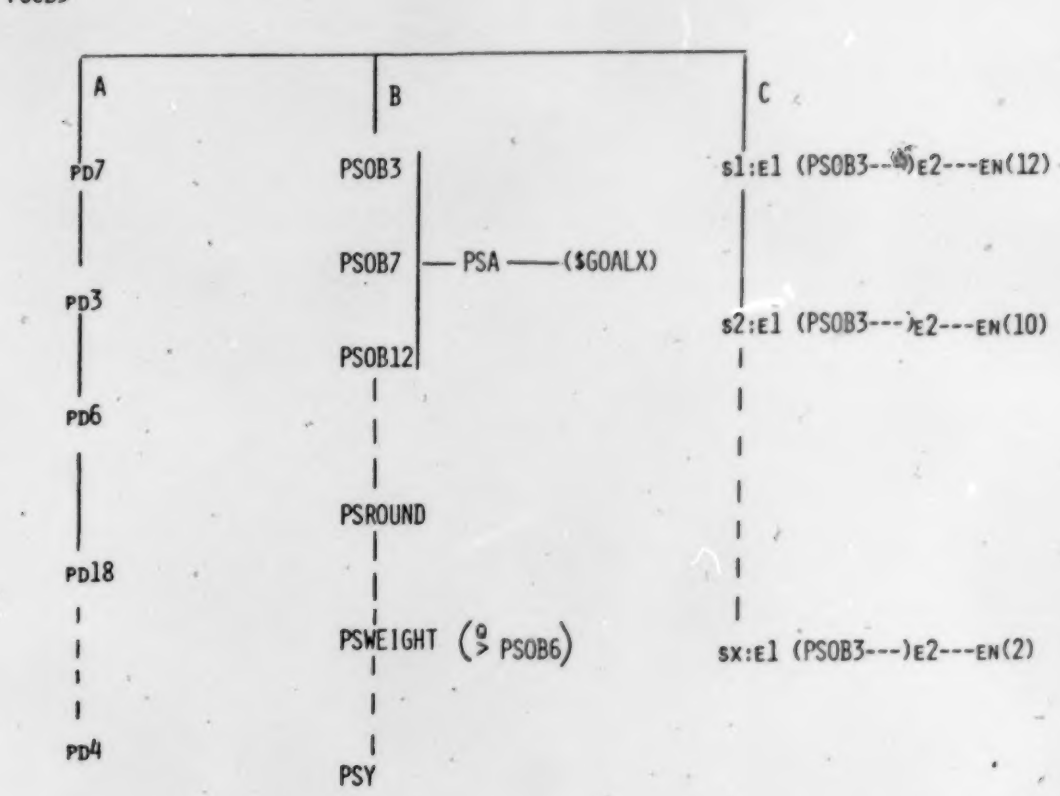
Such continued experience ensures that it is a highly specific version of the sequence which eventually forms the basis for the addition of a new type node to LTM. Here it may become a source of data which may be interpreted as a regression in level of performance. Tasks similar in highly specific detail to those featuring in the environmental interaction giving rise to the type node will be successfully performed. If other versions of what to an observer appear to be the same or highly similar tasks are presented subsequently the performance level will fall since the specificity of the representation at the type node prevents its activation by situations which differ from it at

a detailed level. Such similar situations will not be coped with successfully until additional interaction results in the construction of type nodes adapted to their requirements. The node combination process may, in due course, lead to the construction of a new type node subsuming some or all of these nodes relevant to closely related contexts.

In this paper a brief description has been provided of the relationships between general features of a theory of transition in cognitive development and a broad range of developmental phenomena identified by empirical research. The major conclusion arising from the discussion is that a sufficient transition theory in the form of a self-modifying information processing system constructed in accordance with the general hypothesis that development is a monotone, continuous process is capable of producing a variety of performance data interpretable as evidence of non-monotone, discontinuous development.

FIGURE 1

STRUCTURE OF TYPE NODES IN LTM NETWORK



A DEFINITION LIST

B DESCRIPTION LIST

C EXPERIENCE LIST

FIGURE 2

DETECTION OF REDUNDANT INFORMATION PROCESSING

(1) TIMELINESEGMENT

INITIAL QUANTIFICATION

(PSVS (*GOAL SUBIT SHOES) \ ($GOAL 0 SUBIT SHOES) (QSUBTWO SHOES))

PERCEPTUAL TRANSFORMATION

(PQ (*GOAL) ABS (!GOAL) ABS \ (MOVE SHOES NEW SHOES))

REGISTRATION OF QUESTION

(PQ (*GOAL) ABS (!GOAL) ABS \ (SHOES NEW SHOES (MORE)))

VERBAL ENCODING

(PDVA (SHOES NEW SHOES (MORE)) \ (HEARD MORE) (VALUE SHOES) (VALUE NEW SHOES)
(HEARD SHOES) (HEARD NEW SHOES) (*GOAL GETREL SHOES NEW SHOES))

QUANTITATIVE COMPARISON

(PSQC (*GOAL GETREL SHOES NEW SHOES) \ ($GOAL 0 GETREL SHOES NEW SHOES)
(OLD (SHOES EQUAL NEW SHOES)))

(2) EXPERIENCE LIST

TYPE NODE

PSVS

EXPERIENCE LIST SEQUENCE

PSVS1

(PSVS (*GOAL SUBIT SHOES) \ ($GOAL SUBIT SHOES) (QSUBTWO SHOES))

(PQ (*GOAL) ABS (!GOAL) ABS \ (MOVE SHOES NEW SHOES))

(PQ (*GOAL) ABS (!GOAL) ABS \ (SHOES NEW SHOES (MORE)))

(PDVA (SHOES NEW SHOES (MORE)) (HEARD MORE) (VALUE SHOES) (VALUE NEW SHOES)
(HEARD SHOES) (HEARD NEW SHOES) \ (*GOAL GETREL SHOES NEW SHOES))

(PSQC (*GOAL GETREL SHOES NEW SHOES) \ ($GOAL GETREL SHOES NEW SHOES)
(OLD (SHOES EQUAL NEW SHOES)))

(SALIENCY 0)

(3) TIMELINESEGMENT

(PSVS)(*GOAL SUBIT SHINY BLACK SHOES) \ ($GOAL SUBIT SHINY BLACK SHOES)
(QSUBTWO SHINY BLACK SHOES))

(PQ (*GOAL) ABS (!GOAL) ABS \ (MOVE SHINY BLACK SHOES NEW SHINY BLACK SHOES))

(PQ (*GOAL) ABS (!GOAL) ABS \ (SHINY BLACK SHOES NEW SHINY BLACK SHOES (MORE)))

(PDVA (SHINY BLACK SHOES NEW SHINY BLACK SHOES (MORE)) \ (HEARD MORE)
(VALUE SHINY BLACK SHOES) (VALUE NEW SHINY BLACK SHOES) (HEARD SHINY BLACK SHOES)
(HEARD NEW SHINY BLACK SHOES) (*GOAL GETREL SHINY BLACK SHOES NEW SHINY BLACK SHOES))

(PSQC (*GOAL GETREL SHINY BLACK SHOES NEW SHINY BLACK SHOES) \ ($GOAL 1 GETREL SHINY
BLACK SHOES NEW SHINY BLACK SHOES) (OLD (SHINY BLACK SHOES EQUAL NEW SHINY BLACK SHOES)))

(4) EXPERIENCE LIST

PSVS

PSVS1

(PSVS (*GOAL SUBIT (ANYOF (*INT . 1) (SHINY . 2)) (ANYOF (*INT . 1)
(BLACK . 4)) SHOES) \ ($GOAL SUBIT (ANYOF (*INT X. 1) (SHINY . 2))
(ANYOF (*INT . 1) (BLACK . 4)) (SHOES) (QSUBTWO (ANYOF (*INT . 1) (SHINY . 2))
(ANYOF (*INT . 1) (BLACK . 4)) SHOES))

(PQ (*GOAL) ABS (!GOAL) ABS \ (MOVE (ANYOF (*INT . 1) (SHINY . 2))
(ANYOF (*INT . 1) (BLACK . 4)) SHOES NEW (ANYOF (*INT . 1) (SHINY . 2))
(ANYOF (*INT . 1) (BLACK . 4)) SHOES))

(PQ (*GOAL) ABS (!GOAL) ABS \ ((ANYOF (*INT . 1) (SHINY . 2)) (ANYOF
(*INT . 1) (BLACK . 4)) SHOES NEW (ANYOF (*INT . 1) (SHINY . 2)) (ANYOF
(*INT . 1) (BLACK . 4)) SHOES (MORE)))

(PDVA ((ANYOF (*INT . 1) (SHINY . 2)) (ANYOF (*INT . 1) (BLACK . 4))
SHOES NEW (ANYOF (*INT . 1) (SHINY . 2)) (ANYOF (*INT . 1) (BLACK . 4))
SHOES (MORE)) (HEARD MORE) (VALUE (ANYOF (*INT . 1) (SHINY . 2)) (ANYOF (*INT . 1)
(BLACK . 4)) SHOES) (VALUE NEW (ANYOF (*INT . 1) (SHINY . 2)) (ANYOF (*INT . 1)
(BLACK . 4)) SHOES) (HEARD (ANYOF (*INT . 1) (SHINY . 2)) (ANYOF (*INT . 1)
(BLACK . 4)) SHOES) (HEARD NEW (ANYOF (*INT . 1) (SHINY . 2) (ANYOF (*INT . 1)
(BLACK . 4)) SHOES) \ (*GOAL GETREL (ANYOF (*INT . 1) (SHINY . 2)) (ANYOF (*INT . 1)
(BLACK . 4)) SHOES NEW (ANYOF (*INT . 1) (SHINY . 2)) (ANYOF(*INT . 1) (BLACK . 4))
SHOES))

(PSQC (*GOAL GETREL (ANYOF (*INT . 1) (SHINY . 2)) (ANYOF (*INT . 1) (BLACK . 4))
SHOES NEW (ANYOF (*INT . 1) (SHINY . 2)) (ANYOF (*INT . 1) (BLACK . 4)) SHOES) \
($GOAL GETREL (ANYOF (*INT . 1) (SHINY . 2)) (ANYOF (*INT . 1) (BLACK . 4)) SHOES NEW
(ANYOF (*INT . 1) (SHINY . 2)) (ANYOF (*INT . 1) (BLACK . 4)) SHOES) (OLD ((ANYOF
(*INT . 1) (SHINY . 2)) (ANYOF (*INT . 1) (BLACK . 4)) SHOES EQUAL NEW (ANYOF
(*INT . 1) (SHINY . 2)) (ANYOF (*INT . 1) (BLACK . 4)) SHOES)))

(SALIENCY 7)

(5) NEW REDUNDANCY ELIMINATION PRODUCTION

IF

(($GOAL SUBIT BLACK SHOES) (QSUBTWO BLACK SHOES)) ((MOVE BLACK SHOES NEW BLACK SHOES))
((BLACK SHOES NEW BLACK SHOES (MORE))) ((*GOAL GETREL BLACK SHOES NEW BLACK SHOES)))

THEN

(($GOAL GETREL BLACK SHOES NEW BLACK SHOES) (OLD BLACK SHOES EQUAL NEW BLACK SHOES)))

(IS TO BE PLACED AT NODE PSQC)

FIGURE 3

GENERALISATION OF REDUNDANCY ELIMINATING PRODUCTIONS

(1) EXPERIENCE LIST

TYPE NODE

PSCOUNT

EXPLRIENCE LIST SEQUENCE

COU01

(PSCOUNT (*GOAL QUANTIFY SHOES) \ ($GOAL 0 QUANTITY SHOES) (COUNT TWO SHOES))
(PQ (*GOAL) ABS (%GOAL) ABS \ (COMPRESS SHOES (NEW SHOES)))
(PQ (*GOAL) ABS (%GOAL) ABS \ (SHOES (NEW SHOES) (MORE)))
(PDV1 (SHOES (NEW SHOES) (MORE)) \ (*GOAL GETREL SHOES (NEW SHOES)))
(PSQC (*GOAL GETREL SHOES (NEW SHOES)) \ ($GOAL 0 GETREL SHOES (NEW SHOES))
(OLD (SHOES COUNTEQUAL (NEW SHOES))))

(SALIENCY 10)

(2) DESCRIPTION LIST

TYPE NODE

PSQC

DESCRIPTION LIST SEQUENCE

((PSSUB (*GOAL QUANTIFY SHOES) \ (*GOAL 0 QUANTIFY SHOES) (SUBTWO SHOES))
(PQ (*GOAL) ABS (%GOAL) ABS \ (COMPRESS SHOES (NEW SHOES))) (PQ (*GOAL) ABS
(%GOAL ABS \ (SHOES (NEW SHOFS) (MORE))) (PDV1 (SHOES (NEW SHOES)(MORE)) \ (*GOAL
GETREL SHOES (NEW SHOES))) (PSQC (*GOAL GETREL SHOES (NEW SHOES)) \ ($GOAL 0 GETREL SHOES
(NEW SHOES)) (OLD SHOES SUBEQUAL (NEW SHOES)))))

(3) NEW REDUNDANCY ELIMINATION PRODUCTION

IF

(($GOAL 0 QUANTIFY SHOES) ((ANYOF COUNTTWO SUBTWO) SHOES)) ((COMPRESS SHOES
(NEW SHOES))) ((SHOES (NEW SHOES) (MORE))) ((*GOAL GETRELSHOES (NEW SHOES)))

THEN

($GOAL 0 GETREL SHOES (NEW SHOES)) (OLD (SHOES (ANYOF COUNTEQUAL SUBEQUAL) (NEW SHOES))))

(IS TO BE PLACED AT NODE PSQC)

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